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Expanding the Availability of Lightweight Aluminum Alloy Armor Plate Procured From Detailed Military Specifications

by Kevin Doherty, Richard Squillacioti, Bryan Cheeseman, Brian Placzankis, and Denver Gallardy

ARL-RP-385 **July 2012**

A reprint from the *13th International Conference on Aluminum Alloys (ICAA13)*, pp. 541–546, Pittsburgh, PA, 3–7 June 2012.

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* July 2012	**2. REPORT TYPE** Reprint	**3. DATES COVERED (From - To)** 3–7 June 2012

4. TITLE AND SUBTITLE Expanding the Availability of Lightweight Aluminum Alloy Armor Plate Procured From Detailed Military Specifications	**5a. CONTRACT NUMBER** **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER**
6. AUTHOR(S) Kevin Doherty, Richard Squillacioti, Bryan Cheeseman, Brian Placzankis, and Denver Gallardy	**5d. PROJECT NUMBER** **5e. TASK NUMBER** **5f. WORK UNIT NUMBER**
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory ATTN: RDRL-WMM-F Aberdeen Proving Ground, MD 21005-5069	**8. PERFORMING ORGANIZATION REPORT NUMBER** ARL-RP-385
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)** **11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

A reprint from the *13th International Conference on Aluminum Alloys (ICAA13)*, pp. 541–546, Pittsburgh, PA, 3–7 June 2012.

14. ABSTRACT

For many years, the range of aluminum alloys for armor plate applications obtainable in accordance with detailed military specifications was very limited. However, the development of improved aluminum alloys for aerospace and other applications has provided an opportunity to modernize the Army portfolio for ground vehicle armor applications. While the benefits of offering additional alloy choices to vehicle designers is obvious, the process of creating detailed military specifications for armor plate applications is not trivial. A significant amount of material and testing is required to develop the details required by an armor plate specification. Due to the vast number of material programs that require standardization and with a limited amount of manpower and funds as a result of Standardization Reform in 1995, one typically requires a need statement from a vehicle program office to justify and sponsor the work. This presentation will focus on recent aluminum alloy armor plate specifications that have added capability to vehicle designers' selection of armor materials that offer possible benefits such as lower cost, higher strength, better ballistic and corrosion resistance, improved weldability, etc.

15. SUBJECT TERMS

armor plate specifications, aluminum alloys, procurement, standardization, weldability

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Kevin Doherty
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified	UU	12	**19b. TELEPHONE NUMBER** (*Include area code*) 410-306-0871

13th International Conference on Aluminum Alloys (ICAA13)
Edited by: Hasso Weiland, Anthony D. Rollett, William A. Cassada
TMS (The Minerals, Metals & Materials Society), 2012

EXPANDING THE AVAILABILITY OF LIGHTWEIGHT ALUMINUM ALLOY ARMOR PLATE PROCURED FROM DETAILED MILITARY SPECIFICATIONS

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Keywords: armor plate specifications, aluminum alloys, procurement, standardization, weldability

Abstract

For many years, the range of aluminum alloys for armor plate applications obtainable in accordance with detailed military specifications was very limited. However, the development of improved aluminum alloys for aerospace and other applications has provided an opportunity to modernize the Army portfolio for ground vehicle armor applications. While the benefits of offering additional alloy choices to vehicle designers is obvious, the process of creating detailed military specifications for armor plate applications is not trivial. A significant amount of material and testing is required to develop the details required by an armor plate specification. Due to the vast number of material programs that require standardization and with a limited amount of manpower and funds as a result of Standardization Reform in 1995, one typically requires a need statement from a vehicle program office to justify and sponsor the work. This presentation will focus on recent aluminum alloy armor plate specifications that have added capability to vehicle designers' selection of armor materials that offer possible benefits such as lower cost, higher strength, better ballistic and corrosion resistance, improved weldability, etc.

Introduction

Throughout history standardization has been used to improve products and to save money. From the days of the pyramids we have used standardized dimensions that have contributed to the success of a product or a process. The Romans used standardization in equipping their soldiers. The length of the Roman swords were standardized which allowed for an economical production of quality and quantity while maintaining interoperability. Standardization is based on a concept that relies on developing uniform engineering criteria for producing goods and services that are required by the military. Overall standardization enables material developers and acquirers to achieve materiel compatibility, interchangeability, and commonality between products and services that are developed by the US military and our allies. On a slightly smaller scale, armor materials were standardized by developing armor plate specifications. By standardizing armor plate instead of armor parts, acquisition and maintenance costs can be lowered while increasing our ability to compare different monolithic materials, such as, steel, aluminum, titanium, etc. By utilizing the areal density of each material we are able to compare across different material classes. Armor plate specifications also allow one to separate materials from armor design when developing an armor plate specification. The performances of these armors against specific threats are typically sensitive and are specified in design handbooks.

Whereas armor plate specifications specify the acceptance characteristics of a specific armor plate, therefore, if the lot of material passes the requirements of the plate specification then one has a 95% confidence that the material represented by the lot is the same material as any lot that passes its' (plate specification) requirements.

Aluminum armor can trace its development to Alfred Wilm's discovery in 1909 of the age-hardenable alloy duralumin, known later as dural [1]. Duralumin possessed a high strength-to-weight as compared to other metals, which made it well suited to aircraft applications and within ten years of its discovery, more than 726 tons of duralumin were utilized by the Germans in one year, primarily in airships [2]. Duralumin, which contained copper, manganese and magnesium as alloying elements was eventually designated 17S (2017) and is the progenitor of the 2xxx series of aluminum alloys. Alcoa obtained the rights to produce duralumin after World War I and began research into a number of heat treatable alloy systems – including aluminum-magnesium-silicon (6xxx series), aluminum-magnesium-copper (2xxx series) and aluminum-magnesium-zinc (7xxx series). It was also by this time that aluminum was being considered for armor applications by the US Army.

In 1933, the Director of the Research Institute of Metals at Sendai, Kotaro Honda of the Tohoku Imperial University, published an investigation into 'Bullet Resisting Alloys' where, utilizing a Japanese Army service rifle and a ballistic pendulum, he examined numerous metals and alloys, including copper, lead, brass, mercury, mild and nickel-chrome steels, aluminum and duralumin [3]. His observations that duralumin was stronger than mild steel led the U.S. military to investigate aluminum alloys in the 1930s, and it began using aluminum alloys for armor soon after the United States became a combatant in World War II. Through the war years, the demand for aluminum armor increased due to its successful ballistic performance and the need for lightweight materials for weight-critical applications, such as aircraft and body armor. After World War II, the military began evaluating heavier gage aluminum alloy plate for vehicle armor and studying welding techniques for high-strength aluminum alloys. During that time, a lightweight, air deployable armored personnel carrier was being developed and both steel and aluminum variants, the T117 and T113, respectively, were being evaluated. The aluminum armor, Al 5083, being utilized in the T113 was added to the first general wrought aluminum alloy armor plate specification [MIL-A-46027 (Ord)] which was published on March 6, 1959. Testing and evaluations continued and on 29 April 1959 the experimental, Al 5083 armored, T113E2 was classified as the full track armored personnel carrier M113. Full production of the first aluminum armored vehicle commenced in 1960; however, this did not signify that all the problems with aluminum armor had been resolved and it wasn't until Revision C on June 5, 1964, that the specific chemistries of Al 5083 and Al 5456 alloys were added to the specification and these became known as the first generation aluminum armor alloys [4].

Higher armor piercing resistance aluminum alloys were needed for the hulls of the second generation aluminum armored vehicle, XM551 Sheridan program. Aluminum alloy 7039 provides more mass efficient protection as compared to Al 5083 and a second generation aluminum alloy armor specification [MIL-A-46063 (MR)] [5] covering a heat treatable, weldable wrought aluminum-zinc-magnesium alloy armor plate (Al 7039) was published on August 28, 1963. However, Al 7039 has proven susceptible to stress corrosion cracking (SCC) and weldable, higher strength aluminum alloys have been sought to provide similar ballistic protection as 7039, but with improved SCC resistance. Since the early 1970s, numerous studies were conducted to develop processing techniques and new aluminum alloys that have better ballistic performance and better mechanical properties than Al 7039 with SCC resistance equal

to Al 5083. In 1979, Al 2519 was selected and was subsequently evaluated by the U.S. Army Materials & Mechanics Research Center, the prior incarnation of the present U.S. Army Research Laboratory. The Laminate Armor Program, in support of the Mobile Protected Gun System, performed a number of investigations of Al 2519 as did the Crusader Program as a candidate material and a specification, MIL-A-46192 (MR) [6], was published in 1986. Though both the Armored Gun System (AGS) and the Crusader were cancelled in 1997 and 2002, respectively, the Expeditionary Fighting Vehicle (EFV) Program successfully utilized Al 2519 - the third generation aluminum armor alloy - for hull use in early prototypes before the program was ultimately cancelled in 2011.

For many years, the range of aluminum alloys for armor plate applications obtainable in accordance with detailed military specifications was very limited. However, the development of improved aluminum alloys for aerospace and other applications has provided an opportunity to modernize the Army portfolio for ground vehicle armor applications. This paper will focus on the development of armor plate specifications for five aluminum alloys since 2007 that have added capability to vehicle designers' selection of armor materials for improved performance or decreased cost.

Experimental Procedures

When a new material or alloy is developed and a decision is made to write a detailed specification, one needs to incorporate all the details that are needed to specify that material or alloy and find a repeatable way to test them with a specific level of confidence. An armor material should be tested with a ballistic test, such as a V_{50} [7] with a test projectile that is repeatable and gives the same results when tested against the same material. Once the performance is determined for a specific thickness, the acceptance value is calculated by subtracting two standard deviations (95% confidence level) from the performance value. Typically one tries to get three thickness areas for an ordered thickness of the material which falls within the velocity for the test projectile that is being used. Within each thickness area there should be at least five plates that are being tested. Therefore, the V_{50} acceptance test would be generated from at least 15 plates from that ordered thickness. Minimum mechanical property requirements for the armor plate, such as tensile strength, yield strength, and ductility (percent elongation), would be specific to the material. Additional requirements would include thermal processing, tolerances, and chemistry. Depending on the alloy, one would need to specify a chemistry range or allow the producer to specify a chemistry range. Once that chemistry is used and the material has passed all the first article tests, then that chemistry would be considered that company's "declared chemistry" and future lots/heats of the material could not deviate from that chemistry within limits as directed in the specification. Once all the detailed requirements have been developed and specified in the document the draft would be coordinated for 60 days to the Custodians, Users, and Reviewers both from Industry and Government. Depending on the content and the extent of the received comments a second coordination may be required.

Results

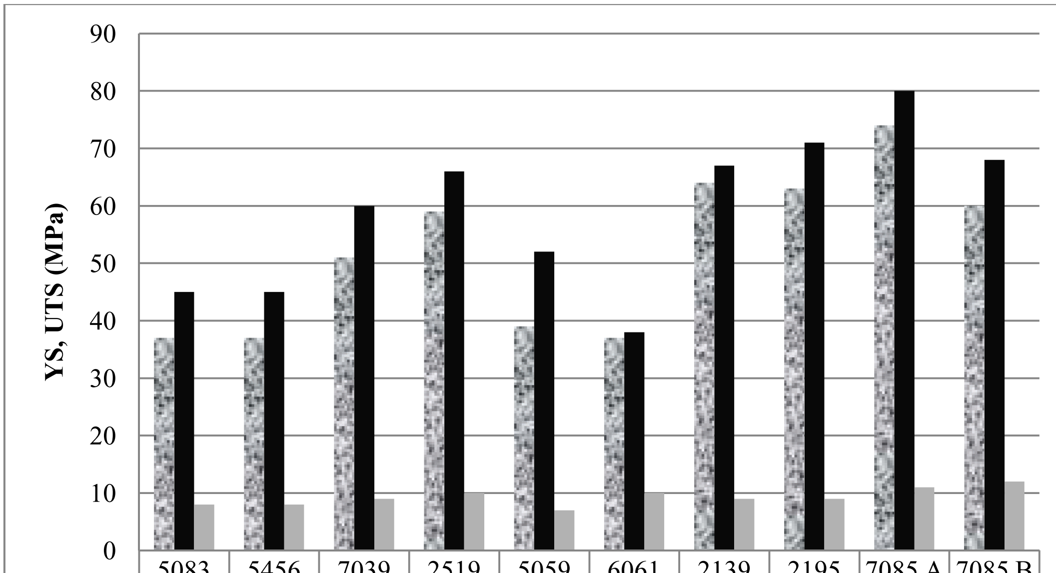
A compilation of the limits for the chemical composition for the aluminum alloys covered by armor plate detailed military specifications are presented in Table I. These limits are typically taken from ASTM B209 or Aluminum Association registered composition limits for aluminum alloys. The left four alloys were covered under existing specifications and the right five alloys were added as part of this development. The minimum acceptable mechanical properties for the

armor plate aluminum alloys are presented in Figure 1. The specimens for these tests are taken in the longitudinal direction. Again, the left four alloys were covered under existing specifications and the right five alloys were added as part of this development. Type A (T711) and Type B (T721) are different tempers for alloy 7085 that have just completed registration with the Aluminum Association in January 2012. Plots for the minimum acceptance ballistic limit using the 20 mm fragment simulating projectile (FSP) at 0° obliquity [8] (figure 2) and the caliber 0.30 armor piercing (AP) M2 projectile at 0° obliquity (figure 3) are shown for the various armor plate aluminum alloys. Figures 2 and 3 plot the V_{50} data versus areal density for comparison purposes; however the specifications use thickness.

TABLE I. Chemical composition limits for aluminum alloy armor plate

Elements	ALLOYS[1,3]								
	5083	5456	7039	2519	5059	6061	2139	2195	7085
Silicon	0.4	0.25	0.3	0.25	0.45	0.40-0.80	0.1	0.12	0.06
Iron	0.4	0.4	0.4	0.3	0.5	0.7	0.15	0.15	0.08
Copper	0.1	0.1	0.1	5.3-6.4	0.25	0.15-0.40	4.5-5.5	3.7-4.3	1.3-2.0
Manganese	0.40-1.0	0.50-1.0	0.10-0.40	0.10-0.50	0.60-1.2	0.15	0.20-0.60	0.25	0.04
Magnesium	4.0-4.9	4.7-5.5	2.3-3.3	0.05-0.40	5.0-6.0	0.8-1.2	0.20-0.80	0.25-0.80	1.2-1.8
Chromium	0.05-0.25	0.05-0.20	0.15-0.25		0.25	0.04-0.35	0.005		0.04
Zinc	0.25	0.25	3.5-4.5	0.1	0.40-0.90	0.25	0.25	0.25	7.0-8.0
Titanium	0.15	0.2	0.1	0.02-0.10	0.2	0.15	0.15	0.1	0.06
Zirconium				0.10-0.25				0.08-0.16	0.08-0.15
Vanadium				0.05-0.15			0.05		
Lithium								0.8-1.2	
Silver							0.15-0.60	0.25-0.60	
Other, max. each	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Other, max. total[2]	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15

[1] Where single units are shown, these indicate the maximum amounts permitted.
[2] The sum of those others metallic elements 0.010 percent or more each, expressed to the second decimal before determining the sum.
[3] The remainder of the composition for each alloy is aluminum.



	5083	5456	7039	2519	5059	6061	2139	2195	7085 A	7085 B
YS	37	37	51	59	39	37	64	63	74	60
UTS	45	45	60	66	52	38	67	71	80	68
%EL	8	8	9	10	7	10	9	9	11	12

Figure 1. Minimum acceptance mechanical properties for aluminum alloy armor plate.

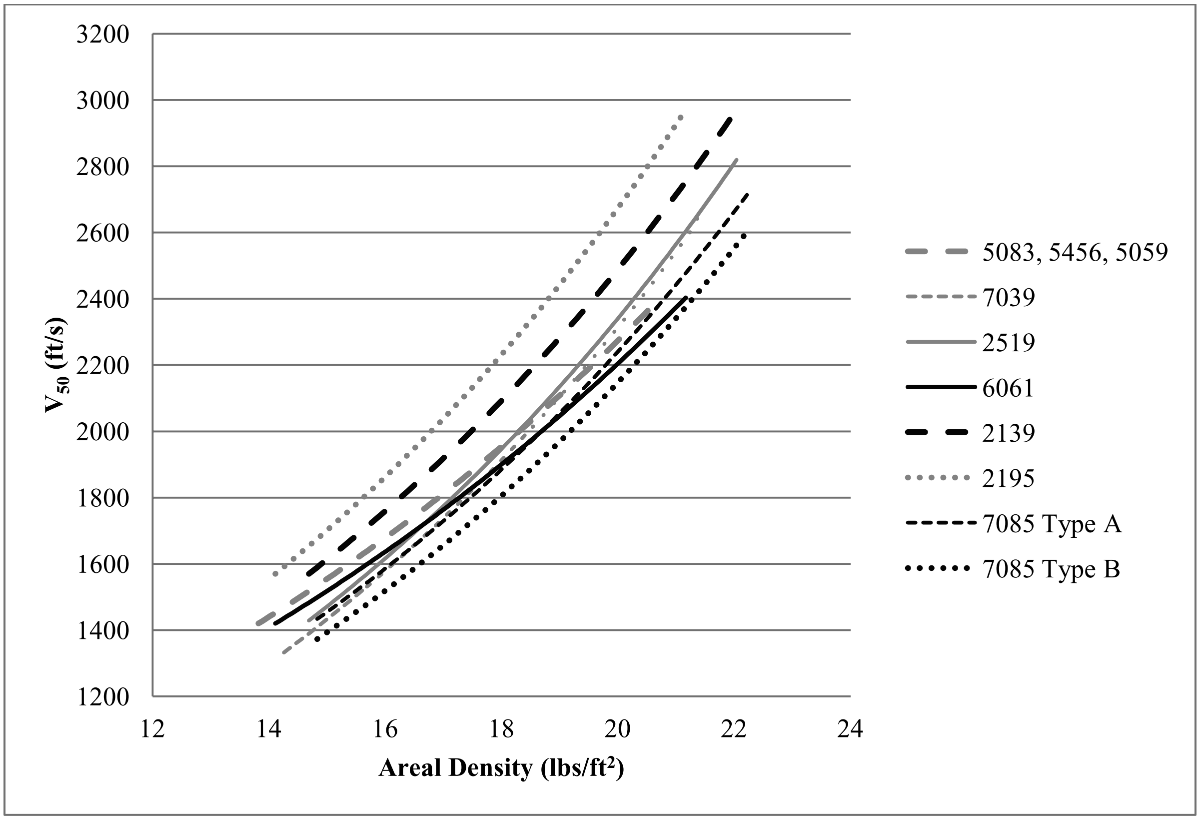


Figure 2. Minimum acceptance ballistic limit - 20 mm FSP at 0° obliquity.

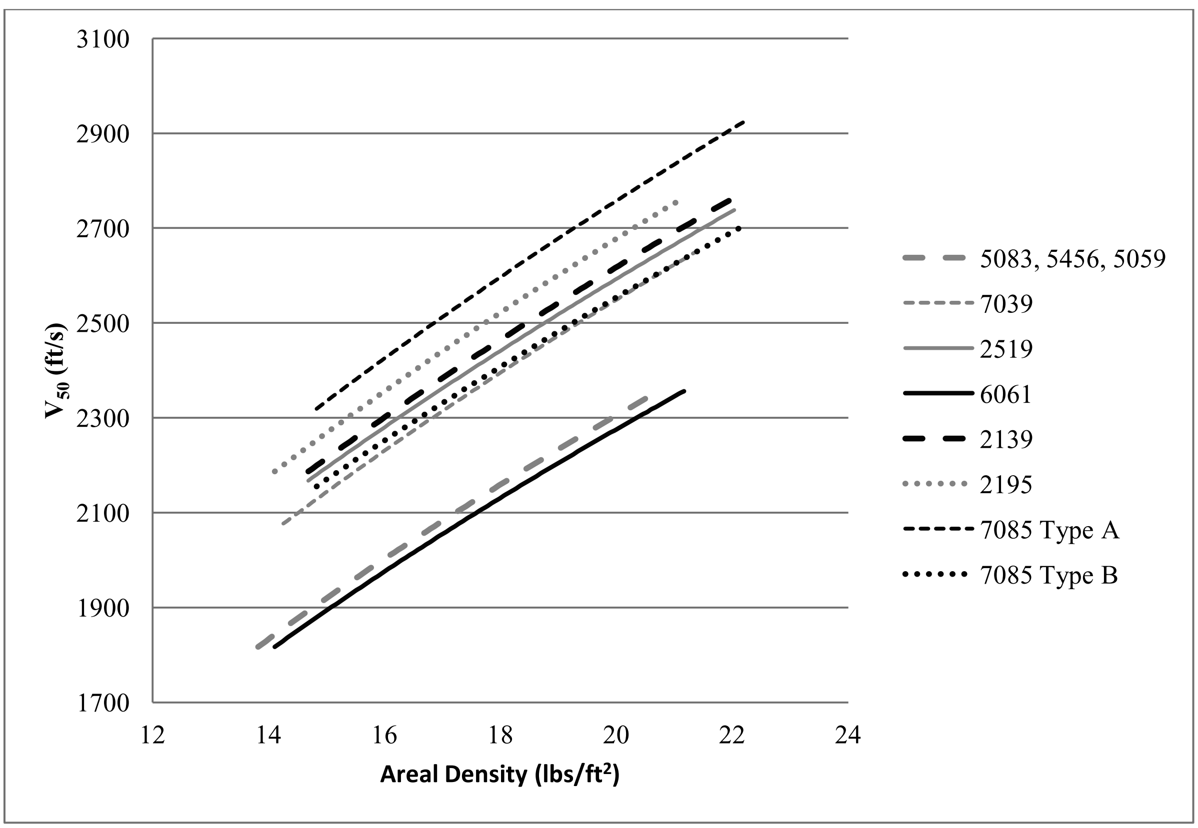


Figure 3. Minimum acceptance ballistic limit – caliber 0.30 AP M2 projectile at 0° obliquity.

Discussion

Five aluminum alloys were qualified for use in military armor plate applications and have been incorporated in four specifications, three new and one updated. MIL-DTL-32262 [9] was created for Al 6061 to allow a low-cost, equal ballistic replacement for Al 5083 in limited applications, such as appliqués. MIL-DTL-46027K [4] was updated to include Al 5059 which can be substituted for Al 5083 providing superior strength and ballistic performance without sacrificing corrosion resistance or weldability. Al 5059-H131 [10] does offer enhanced ballistic performance over Al 5083-H131 even if the specification does not show this in the minimum acceptance limits in figures 2 and 3. MIL-DTL-32341 [11] was generated for the high performance aerospace alloys (Al 2139 and Al 2195) to be used in armor applications. These alloys offer significantly enhanced ballistic performance and strength. Currently, this is an unweldable specification such that the armor plate can only be used in appliqué situations. MIL-DTL-32375 [12] was created for Al 7085 [13] in two different tempers, a high strength temper (Type A) for enhanced ballistic protection and a second temper (Type B) for improved blast protection.

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